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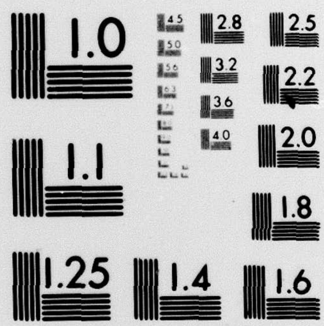

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6 WAVE PROPAGATION IN THREE-DIMENSIONAL INELASTIC MEDIA.

9 Final Report. 26 Jan 76 - 15 Sep 79,

by

10 T. C. T. Ting

11 11 December 1979

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The research supported by the Army grant was to study some aspects of three-dimensional waves in inelastic media. Inelastic media include elastic-plastic materials and viscoelastic solids. This report contains a summary of the results obtained from this investigation.

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I. PROBLEM STUDIED AND RESULTS OBTAINED UNDER THE ARMY RESEARCH GRANT

The research supported by the Army was to study some aspects of three-dimensional waves in inelastic media. Inelastic media include elastic-plastic materials and viscoelastic solids. The following is a summary of the results obtained.

Basic information needed in analyzing wave propagation in three-dimensional media are the eigenvectors (or the polarization vectors) of the acoustic tensor and the transport equations which determine the growth or decay of a discontinuity. These were obtained for a fairly general anisotropic elastic-plastic media in which the eigenvectors in the plastic state were expressed explicitly in terms of the elastic acoustic tensor [1]. This expression makes it easier to calculate numerically the eigenvectors in the plastic state. The discontinuity in acceleration across the singular surface is proportional to this eigenvector regardless of whether the singular surface is an elastic-elastic, plastic-plastic or elastic-plastic interface. We also obtained the ray velocity and the transport equations for the growth or decay of the discontinuity along the ray. The possibility of shock waves in a plastic region is explored. Finally, the general results are specialized for isotropic elastic-plastic solids.

With the general results obtained in [1], we then study basic problems needed for three-dimensional waves. The first is the wave speeds. Although the plastic wave speed in one-dimensional media is well-known, the plastic wave speeds in three-dimensional media have not been looked at carefully, at least not quantitatively. In a one-dimensional wave, the plastic wave speed can become zero when the tangent modulus of the stress-strain curve vanishes. A typical example is the ideally plastic solids. In three-dimensional media, the plastic wave speeds depend not only on the tangent modulus, but also on

the direction of propagation, even when the material is isotropically work-hardening. However, regardless of the direction of propagation, it was found that the difference between c_f, the fast plastic wave speed, and c_1, the fastest elastic wave speed, is no more than 35% of c_1 for the von Mises' materials and 29% for the Tresca's materials [2,3]. For materials which are not ideally plastic and for loading of a magnitude such that the tangent modulus at the stress state is not nearly zero, the difference is smaller. The difference will be even smaller if the direction of propagation is not in the direction of the minimum wave speed. In fact, one can always choose a family of directions such that c_f and c_1 are identical. These results apply also to ideally plastic solids.

The significance of this finding is that when we analyze wave propagation in a thin rod as a three-dimensional circular cylinder, the difference between c_1 and the statistical average of c_f for all directions will probably be within 10% of c_1. Since the precursor wave front propagates at the fastest wave speed, this implies that the plastic wave front will propagate at a speed within 10% of the elastic wave front. Thus the phenomenon observed in the experiments that the plastic wave front propagated at the elastic wave speed might not be entirely due to the rate effects as widely believed. The approximation of three-dimensional circular cylinder by a one-dimensional rod may also be responsible, if only partially, for the phenomenon.

The second basic problem is the reflection and transmission of a wave front at an interface between two different materials. A special case of this problem is the reflection of a wave front from a boundary which may be fixed or stress free [4]. Near the point of reflection, the geometry of the boundary and the incident wave front is not important as far as the

acceleration waves are concerned. Therefore, we analyzed the reflection of acceleration waves from the surface of a semi-infinite elastic-plastic medium. Depending on the nature of the incident waves and the incident angle, there may be one to four reflected waves generated. The analyses can predict the number and the speeds of waves reflected and also identify whether the regions behind the reflected waves are either elastic or plastic. This information serves useful guides for solving numerically three-dimensional wave propagation problems.

Another basic problem for wave propagation in elastic-plastic media is the question of discrepancies between the rate-independent theory and the experimental observations. The rate-effect has been considered as the main cause of the discrepancies but there are also other factors, such as the three-dimensional effect. To study this effect, we consider a three-dimensional numerical solution to wave propagation in a semi-infinite circular cylindrical rod of elastic-plastic rate-independent material due to a uniformly distributed axial load applied at the end of the rod [5]. The experiments showed that the wave front propagated at the speed of elastic bar velocity c_o while the rate-independent one-dimensional theory predicts that the disturbance propagates at the plastic wave speed c_p. The three-dimensional numerical solution reveals that while the stress history at a station 10 radii from the impact end agrees qualitatively with the one-dimensional theory, the wave front travels at a speed somewhere between c_o and c_p. In view of the oscillatory nature of the numerical solution, it is difficult to pinpoint the exact arrival time of the wave front. However, the wave front definitely travels faster than c_o.

In [1], we discussed the possibility of generating a shock wave in three-dimensional elastic-plastic media. Before we proceeded to study in more detail the nature of three-dimensional shock waves, we looked at the

existing publications on one-dimensional shock waves and discovered some interesting results. Firstly, while the infinitesimal deformation theories are adequate if the strains are small, they lead to physically unacceptable phenomena if the impact velocity is transonic or supersonic [6]. Secondly, one may define the growth of a shock wave by the growth in the discontinuity in the velocity across the shock wave as the shock wave propagates. One may also define the growth of a shock wave by the growth in the discontinuity in the stress, strain or the entropy. It turns out that while one definition predicts the growth of the shock wave, the other definition may predict its decay [7].

The problem of three-dimensional shock waves in solids appears to be much more complicated than we had anticipated. We were not able to accomplish the study during the period of the grant. However, we were able to re-examine the three-dimensional shock waves in elastic fluids [8].

Knowing that we could not complete the study on three-dimensional shock waves in solids, we studied the problem of wave propagation normal to the layering of a periodically layered elastic or viscoelastic medium. Even though many approximate theories have been proposed for wave propagation in a composite, there appears to be no reliable way to predict satisfactorily the transient response in the region which is neither far away from the impact end nor near the wave front. The same is true for transient waves in a finite layered medium. We proposed a theory which, from a practical point of view, can determine satisfactorily the transient solution in a region which can be near or far away from the impact end [9]. The fundamental idea of the theory is to replace the layered medium by an "equivalent" homogeneous, linear viscoelastic medium whose dynamic response is identical to that of the layered medium at points which are the

centers of the odd layers. Since wave propagation in a homogeneous, linear viscoelastic medium can be solved easily by many known numerical schemes, one can solve any transient wave propagation problem in semi-infinite or finite layered medium [10] by the present theory. Several numerical examples are obtained and compared with the exact solutions by the ray theoy. The agreement between the two solutions is extremely satisfactory.

II. List of Publications

[1] "Shock Waves and Weak Discontinuities in Anisotropic Elastic-Plastic Media," in The Propagation of Shock Waves in Solids, ASME, AMD-Vol. 17, ed. by Eric Varley, 1976, 41-64.

[2] "Wave Speeds and Slowness Surface in Elastic-Plastic Media obeying Tresca's Yield Condition," Advances in Engineering Science, NASA CP-2001, 1976, 85-94. (Proceedings of the 13th Annual Meeting of the Society of Engineering Science held in Hampton, Va., Nov. 1-3, 1976).

[3] "Plastic Wave Speeds in Isotropically Work-Hardening Materials," J. Appl. Mech., Vol. 44, No. 1, March 1977, 68-72.

[4] "Reflection of Acceleration Waves in an Elastic-Plastic Medium," J. Appl. Mech., Vol. 45, No.1, March 1978, 51-59. (with J. C. Cizek).

[5] "Plastic Wave Propagation in a Circular Cylindrical Rod," Under preparation. (with J. W. Swegle).

[6] "On Supersonic and Transonic Impact of Solids," ed. by Kozo Kawata and Jumpei Shioiri, Springer-Verlag, N. Y., 1978, 305-310. (Proceedings of IUTAM Symposium held in Tokyo, Japan on Aug. 24-27, 1977).

[7] "Further Study on One-Dimensional Shock Waves in Nonlinear Elastic Media," Q. Appl. Math. To appear.

[8] "Intrinsic Description of Shock Waves in Three-Dimensional Nonlinear Elastics Fluids." Under preparation.

[9] "A Theory of Viscoelastic Analogy for Wave Propagation Normal to the Layering of a Layered Medium," J. Appl. Mech., Vol. 46, No. 2, June 1979, 329-336. (with Isao Mukunoki).

[10] "Transient Wave Propagation Normal to the Layering of a Finite Layered Medium," Int. J. Solids Structures. To appear. (with Isao Mukunoki).

III. List of Participating Scientific Personnel and Degrees Awarded

John Cizek, Ph.D

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